Soybean Effects on Soil Nitrogen Availability in Crop Rotations

Matias B. Vanotti and Larry G. Bundy*

ABSTRACT

Soybean [*Glycine max* (L.) Merr.] production contributes significantly to the N supply for a following corn (*Zea mays* L.) crop, even though soybean N budget studies indicate that N removed in grain may substantially exceed biological fixation. Information on the N status of cereal crops during the 2nd yr following soybean may help resolve this issue. This study reports on N effects of soybean on yield response of succeeding cereal crops and soil N availability based on data from a 15-yr crop rotation experiment (1977–1991) on a Rozetta silt loam soil (Typic Hapludalfs) at Lancaster, WI. We evaluated the yields of corn and oat (*Avena sativa* L.) succeeding soybean and alfalfa (*Medicago sativa* L.) in corn–soybean–corn–oat–alfalfa (CSCOM) and corn–corn–oat–alfalfa–alfalfa (CCOMM) crop rotations. Fertilizer N (0, 56, 112, and 224 kg ha^{-1}) was applied only to corn, but NO_3-N carryover usually affected oat yields as well. The legume fertilizer N replacement values based on check plot yields and the response function of 3rd-yr corn in a corn–corn–corn–alfalfa–alfalfa sequence, were equivalent to 153 and 36 kg N ha^{-1} for the 1st and 2nd yr after alfalfa, respectively, and 75 kg N ha^{-1} for the 1st yr after soybean. In the 2nd yr after soybean (CSC<u>O</u>M), oat yields were significantly lower than following corn in the CC<u>O</u>MM rotation. Preplant soil NO_3 and oat N uptake (1987–1991) indicated that oat yield differences were due to lower soil N availability in the CSCOM rotation. The average soybean effect on soil N availability in the 2nd yr was equal to a soil N debit of 36 kg N ha^{-1}. This indicates that part of the N contribution of soybean to 1st-yr corn is realized at the expense of subsequent reductions in soil N availability.

Crop sequence studies show that soybean affects the N requirements of a following corn crop. Numerous reports for the U.S. Midwest indicate that soybean harvested for grain can supply an average of 45 to 67 kg N ha^{-1} (1 to 1.5 kg ha^{-1} of N for every 60 kg ha^{-1} of soybean harvested) to a following corn crop (Shrader, 1973; Baldock et al., 1981; Voss and Shrader, 1984; Schepers and Mosier, 1991; Bundy et al., 1993). These values represent an apparent legume-N contribution or legume-N credit usually estimated through a fertilizer-N replacement value approach. Fertilizer N replacement value is defined as the amount of fertilizer N required in a corn–corn sequence to produce yields equivalent to those in a legume–corn sequence without fertilizer N (Hesterman, 1988). Whether the positive yield responses that are frequently observed where corn follows soybean are due solely to residual symbiotically derived N or include other stimulatory effects of soybean is unclear (Welch, 1985; Cruse et al., 1985). Fertilizer-N equivalence estimates may also include detrimental effects of monoculture (Benson, 1985; Turco et al., 1990; Vanotti et al., 1995), since responses have usually been evaluated by comparison with the yield performance of continuous corn (Lory et al., 1989; Peoples and Craswell, 1992). In most crop sequence–N fertilizer experiments, however, the addition of N can compensate for a large part of the yield differences between legume-cereal and cereal–cereal sequences (Welch, 1985), indicating that increased soil N availability has a major role in the yield-enhancing effect associated with soybean. This observation supports the presumption that a fraction of the symbiotically fixed N_2 in a soybean crop will subsequently accrue in the soil and benefit a succeeding crop. In contrast, soybean N budget studies indicate that the export of N in the seed may substantially exceed biological fixation (Ebelhar and Welch, 1981; LaRue and Patterson, 1981; Heichel and Barnes, 1984; Herridge and Bergersen, 1988; Peoples and Craswell, 1992), suggesting that soybean production is depleting rather than enhancing soil N reserves. Blackmer et al. (1988) reported a more rapid decrease in soil organic N for corn–soybean sequences vs. continuous corn in two long-term rotation experiments in Iowa, which is consistent with the results from soybean N budget studies.

If soybean grain production results in a net removal of N from the soil, the reasons for the reduced response to applied N usually observed in subsequent cereal crops are not clear. Our objective was to examine sequence effects on soil N availability and crop N uptake for cereal crops grown during the 2nd yr following soybean in a long-term crop rotation experiment. Evaluation of information from the 2nd-yr crop following soybean may contribute to an improved understanding of the soybean rotation effect.

MATERIALS AND METHODS

The experiment was conducted at the University of Wisconsin Agricultural Research Station near Lancaster, WI (42°51′ N, 90°42′ W), on a Rozetta silt loam soil (fine, silty, mixed, mesic Typic Hapludalfs). The study was part of a long-term legume–cereal rotation experiment, which was established in 1967 (Higgs et al., 1976; Baldock et al., 1981). Crop yield data included in this report were obtained between 1977 and 1991 from two 5-yr crop rotations included in the main experiment. Crop species were corn (*Zea mays* L.; Northrup King PX20, Pioneer 3780, Pioneer 3615, or Pioneer 3475); oat (*Avena sativa* L.; 'Dal', 'Froker', or 'Ogle'); alfalfa (*Medicago sativa* L.; 'Vernal', 'Apollo', 'Blazer' or 'Legend'); and soybean [*Glycine max* (L.) Merr.; 'Corsoy', 'Hodgson', 'Elgin', or 'Trelay 264']. These species were combined in corn–soybean–corn–oat–alfalfa (CSCOM) and corn–corn–oat–alfalfa–alfalfa (CCOMM) crop sequences. Yield data corresponding to 3rd-yr corn in a CCCMM sequence were used as a control treatment to evaluate corn response to N rate in the CSCOM and CCOMM rotations. Four levels of N fertilizer: 0, 56, 112, and 224 kg N ha^{-1} were applied as ammonium nitrate before spring tillage to every phase of corn each year (1977–1991), but no fertilizer N was applied to any other crop. Every crop rotation–phase combination was grown annually in a 6.1- by 36.6-m main plot. These main plots were divided to accommodate the N treatments (subplots). The experimental design was a split plot, where crop rotation phases were assigned to main plots at the start of the experiment in a randomized complete block design with two replicates. Each rotation–phase treatment was repeated on the same plot every 5 yr (cycle).

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Abbreviations: CCCMM, corn–corn–corn–alfalfa–alfalfa; CCOMM, corn–corn–oat–alfalfa–alfalfa; CSCOM, corn–soybean–corn–oat–alfalfa; FRV, fertilizer replacement value. *Underscores in a rotation code indicate the phase of the rotation under discussion.*

The plots were chisel plowed in the fall and disked in the spring. The planting rates were 59 000 to 72 000 seeds ha^{-1} for corn, 108 kg ha^{-1} for oat, 13.4 to 16.8 kg ha^{-1} for alfalfa, and 84 kg ha^{-1} for soybean. Corn and soybean were planted in 76-cm rows in May (1–15 May), and alfalfa and oat were drilled simultaneously in 18-cm rows in April (6–21 April). Adequate P and K was maintained for all crops throughout the experiment. Plots were limed to maintain a pH of 6.9. Soil tests (Schulte et al., 1987) for pH, available P (mg kg^{-1}), and exchangeable K (mg kg^{-1}) in 1990 N check plots (0- to 20-cm depth) were 6.9, 21, and 150 in CSCQM and 6.7, 27, and 173 in CCQMM, respectively. Herbicides, insecticides, and usually two cultivations were used to control corn and soybean pests (Baldock et al., 1981; Vanotti et al., 1995). Alfalfa was harvested on a three-cut system, and grain harvests were made in the other three crops. The yields of corn, oat, soybean, and alfalfa are reported at 155, 140, 140, and 0 g kg^{-1} moisture content, respectively.

Soil and plant N tests were performed during a complete rotation cycle in 1987 through 1991 to evaluate soil N availability for a 2nd-yr cereal crop following soybean and a 3rd-yr cereal crop following alfalfa in CSCQM and CCQMM. Profile soil NO_3–N and NH_4–N concentrations were measured in the spring (6–23 April) in 30-cm increments to a depth of 90 cm. At physiological maturity, oat was harvested to measure total plant N uptake. Specific experimental procedures for soil and plant N determinations were previously reported by Vanotti and Bundy (1994). Soil organic C and N concentrations and mineralizable N were measured in 1990 N check plots to a depth of 20 cm. Soil organic C was determined using a modified Mebius procedure (Yeomans and Bremner, 1988), total soil organic N was determined by Kjeldahl digestion (Nelson and Sommers, 1972), and mineralizable N was determined in 40-wk aerobic incubation at 35°C (Bundy and Meisinger, 1994).

Data were subjected to analyses of variance for the appropriate experimental design (SAS Institute, 1988). Significant differences among N × rotation treatment means were evaluated using a least significant difference (LSD) test at the 0.05 level, computed with variation (mean square error) among subplots (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Corn grain yields obtained in the Lancaster crop rotation study for the period from 1977 to 1991 (Table 1) illustrate the effect of legume crops on corn yield response to applied N that is typical of many crop rotation experiments throughout the midwestern USA. Response data show that an alfalfa crop supplied most of the N required by a following corn crop, and a lower but still substantial amount of the total N requirement of 2nd-yr corn in the sequence (Table 1). The net effect of legumes in reducing the fertilizer-N needs of subsequent corn is also evident in the soybean–corn sequence. With increased years of corn following alfalfa, the yields of unfertilized corn declined, while the yield responses to applied N increased proportionally. Addition of N removed most of the corn yield differences among rotation–phase treatments (Table 1). Fertilizer-N replacement values (FRV) were calculated to quantify the relative legume N effect on succeeding corn, based on the yield response function for 3rd-yr corn in the CCCMM rotation (Table 1). The FRVs were calculated by equating this response function to the average yields obtained at the 0 kg N rate, and solving for N.

The choice of rotated corn (CCCMM) for the control treatment instead of the continuous corn sequence in this experiment was due to detrimental effects of long-term monocropping on soil characteristics such as soil organic N content and N supplying capability (Vanotti et al., 1995), distorting both the N response curve and derived FRV. For example, yields of unfertilized continuous corn were halved in <10 yr, while yields of 3rd-yr corn without N addition in the CCCMM rotation remained constant throughout the study (1967–1991). Results of the FRV calculations showed that the apparent N contribution of soybean to the first phase of corn was about half the amount contributed by alfalfa, but twice the N value corresponding to 2nd-yr corn following alfalfa (Table 1). Both soybean grain yields and alfalfa dry matter yields were not affected by N rates applied to corn, averaging 2.60 and 9.31 Mg ha^{-1}, respectively.

Yield patterns and N responses of cereal crops after soybean were markedly different from those observed in the alfalfa–cereal sequence (Fig. 1). The greater apparent N contribution of soybean to 1st-yr corn relative to CCOMM (Fig. 1a) contrasts with the yield responses of unfertilized oat in the subsequent year (Fig. 1b). Effects of crop rotation, corn N treatments, and their interaction on oat grain yields were significant at the $P < 0.01$ probability level (Table 2). Where no N fertilizer was previously applied, oat yields in the soybean sequence (CSCQM) were 0.53 Mg ha^{-1} (26%) lower than CCQMM (1977–1991 average). As with corn, the sequence effect on oat yields decreased with increasing levels of available N, in this case from carryover fertilizer N. Yield differences between crop rotations were not due to long-term N rate effects, since the same amounts of N were applied in both rotations. Results of studies in Minnesota (Crookston et al., 1991) showed that 2nd-yr corn yields in soybean–corn rotations were significantly lower than in continuous corn. These yield patterns were somewhat surprising, since a gradual

Table 1. Effect of legume and fertilizer N on corn yields in legume–cereal crop rotations, Lancaster, WI, 1977 to 1991.

Crop rotation and phase†	N rate applied to corn, kg ha^{-1}: 0	56	112	224	P>F‡	CV	FRV§
	Corn yield, Mg ha^{-1}					%	kg N ha^{-1}
CSCOM	7.61a¶	8.10b	8.41b	8.16b	0.006	12.7	75
CCOMM	8.06a	8.46a	8.53a	8.46a	NS	11.1	153
CCOMM	6.79a	7.82b	8.31c	8.38c	0.001	13.2	36
CCCMM	4.90a	7.28b	7.96c	8.10c	0.001	12.9	0

† C = corn, S = soybean, O = oat, M = alfalfa. Underscores indicate the phase of the rotation for which data are presented.
‡ $P > F$: the probability that the tabular F-ratio exceeds the F-ratio calculated by analysis of variance. NS, not significant at $P \leq 0.10$.
§ FRV, fertilizer N replacement value of the preceding legume. Estimates are based on the N response function (Mitscherlich–Spillman model) for the control, 3rd-yr corn following alfalfa (CCCMM): $Y = 8.14 - 3.24 \exp(-0.02413N)$, $R^2 = 1.00$.
¶ Within rows, means followed by the same letter are not significantly different by LSD at the 0.05 level. Means are averages of 15 yr and two replications.

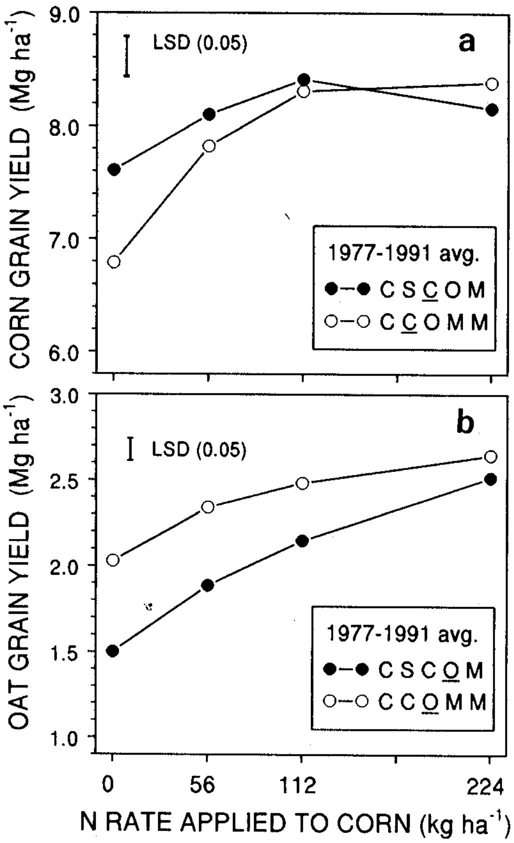

Fig. 1. Soybean effect on (a) subsequent corn grain yields and (b) subsequent oat grain yields at varying levels of N fertilizer applied to corn in the Lancaster, WI, rotation study. Each point is a mean of 30 observations over 15 yr. LSD applies for comparisons between any two means.

decrease in legume N contribution and yields of subsequent cereal crops in succeeding years after a legume would be expected (e.g., alfalfa–corn sequence in Table 1).

The lower oat yields in the CSCOM rotation relative to the CCOMM rotation (Fig. 1b) appear to be due to a soybean effect rather than to a difference in soil N availability related to the number of years of alfalfa in the two rotations. This is supported with previous data obtained in this experiment (1972–1976), showing that unfertilized oat yields were similar in three crop sequences involving corn, oat, and alfalfa whether the sequences contained 1, 2, or 3 yr of alfalfa (Table 3). However, oat yields were lower in the CSCOM sequence. Further evidence that the soybean effect on oat yield is due to short-term organic N cycling rather than to long-term effects on soil organic matter characteristics is provided by the nearly identical soil organic C and N concentrations in the two rotations in 1990. Average (SE) organic C and N concentrations in the CSCOM rotation were 16.6 (0.7) and 1.33 (0.04) g kg^{-1}, respectively. Corresponding values for the CCOMM rotation were 16.3 (0.1) and 1.33 (0.04) g kg^{-1}, respectively.

Measurements taken in 1987 through 1991 showed that both oat N uptake and soil NO_3–N content in the 0- to 30-cm depth were significantly ($P < 0.01$) affected by crop rotation (Table 2), but the effect of rotation on soil NO_3–N content in the 30- to 60-cm and 60- to 90-cm depths, or soil NH_4–N content at all depths, was not significant (Vanotti and Bundy, 1994). Data in Fig. 2 support the conclusion that differences in N availability caused the rotational differences in oat yields illustrated in Fig. 1b, since N uptake and soil NO_3 differences followed the same pattern and were eliminated at the high N rate. Crop rotation effects on soil NO_3–N reflect changes in the mineralizable fractions of soil organic N pools. Long-term aerobic incubations in the laboratory showed that the av-

Table 2. Analysis of variance summary for the effects of crop rotation and fertilizer N applied to corn on yields of oat and the preceding corn crop (1977 to 1991), and on spring soil NO_3–N content before seeding oat and oat total N uptake (1987 to 1991).†

Source of variation	df	Corn yield	Oat yield	Oat N uptake	Soil NO_3–N (0 to 30 cm)
		Mean square values‡			
Blocks	1	0.042	0.743	6	391
Rotation (R)	1	3.825	7.873***	11 992***	5 628***
Year in a cycle (Y)§	4	49.347***	7.172***	13 996***	35 145***
R × Y	4	1.035	0.061	2 253*	370
Error *a*	9	2.589	0.311	432	246
N rate (N)	3	23.249***	7.076***	12 664***	16 010***
R × N	3	4.531***	0.448***	692	1 219**
Y × N	12	3.514***	0.200**	311	5 610***
R × Y × N	12	0.580	0.117	352	1 012**
Error *b*	30	0.498	0.066	329	277
Cycle (C)	2	1.852	0.585**		
R × C	2	0.333	0.269		
Y × C	8	52.598***	4.110***		
N × C	6	2.051	0.272*		
R × Y × C	8	3.043**	0.216*		
R × N × C	6	0.578	0.089		
Y × N × C	24	1.468	0.096		
R × Y × N × C	24	0.436	0.055		
Error *c*	80	1.055	0.100		
CV, %		13.1	14.4	17.3	24.5

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Crop rotation: CSCOM and CCOMM (where C = corn, S = soybean, O = oat, and M = alfalfa; underscores indicate the phases under discussion). Rotation phase × N level means are shown in Fig. 1 for grain yields and in Fig. 2 for soil NO_3–N and oat N uptake.
‡ Based on Mg ha^{-1} for corn and oat grain yields, kg ha^{-1} for oat N uptake and soil NO_3–N.
§ Rotation phase treatments were repeated on the same plots every 5 yr.

Table 3. Oat yields in four crop rotations, Lancaster, WI, 1972 to 1976.

Crop rotation or source of variation†	df	N rate applied to corn, kg ha^{-1} 0	84	168	336
		Oat yield, Mg ha^{-1}			
COMMM§		1.63‡	1.77	2.15	2.16
CCOMM		1.67	1.80	2.25	2.25
CCCOM§		1.61	1.76	2.12	2.39
CSCOM		1.28	1.55	1.98	2.20
ANOVA		$P>F$¶			
Crop rotation	3	0.045	NS	NS	NS
CSCOM vs. others	1	0.006	0.056	NS	NS
CSCOM vs. CCCOM	1	0.029	NS	NS	NS
COMMM vs. CCCOM	1	NS	NS	NS	NS
CV, %		19.9	17.6	19.2	18.9

† C = corn, S = soybean, O = oat, M = alfalfa. Underscores indicate the phase of the rotation for which data are presented.
‡ Means are averages of 5 yr and two replications.
§ Rotation discontinued in 1977.
¶ $P > F$ at the 0.10 significance level.

erage amounts of N mineralized from soils in the oat plots of the CCOMM and CSCOM rotations were 159 and 142 mg kg^{-1}, respectively, and were significantly different ($P < 0.01$, CV = 5.3%). This difference in mineralizable N is equivalent to 51 kg N ha^{-1}. When averaged across years (1987–1991) and the two lower N rates (0 and 56 kg N ha^{-1}), preplant soil NO_3–N contents in CSCOM and CCOMM, respectively, were 34 and 59 kg N ha^{-1} in the 0- to 30-cm depth and 62 and 98 kg N ha^{-1} in the 0- to 90-cm depth. Corresponding oat N uptake values were 69 kg N ha^{-1} (CSCOM) and 102 kg N ha^{-1} (CCOMM). Thus, most of the difference in oat N uptake between crop rotations was accounted for by differences in the amount of soil NO_3–N present in the 0- to 30-cm depth at the beginning of the growing season, and additional absorption of subsoil NO_3–N or mineralized N probably accounted for the remainder of the difference in N recovered by oat. A 3-yr experiment on a Plano silt loam (fine-silty, mixed, mesic Typic Argiudolls) at Janesville, WI (Bundy et al., 1993), showed that total N uptake of 1st-yr corn following soybean receiving a 0 N rate was always higher than those of continuous corn (mean = 188 and 121 kg N ha^{-1}, respectively), whereas N uptake of 2nd-yr corn was the lowest (mean = 104 kg N ha^{-1}), which is consistent with results shown in Fig. 2. These data suggest that part of the yield-enhancing effect of soybean on a 1st-yr cereal crop is realized at the expense of subsequent reductions in soil N availability.

The average soybean effect on soil N availability in the 2nd-yr cereal crop (CSCOM) compared with that in 3rd-yr cereal after alfalfa (CCOMM) was equal to a soil N debit of 36 kg N ha^{-1}. The control sequence phase (CCOMM) used to measure this soil-N debit is equivalent to 3rd-yr corn in CCCMM (Table 1), and corn N fertilizer recommendations (before legume-N adjustment) are usually based on ≥3 yr of continuous corn (Voss, 1969). Our data indicate that a preplant soil NO_3 test can be used to confirm the lower N availability that may occur in the 2nd yr after soybean.

While the specific mechanisms responsible for the reduced N availability to 2nd-yr cereal crops following soybean are unknown, previous work suggests that this phe-

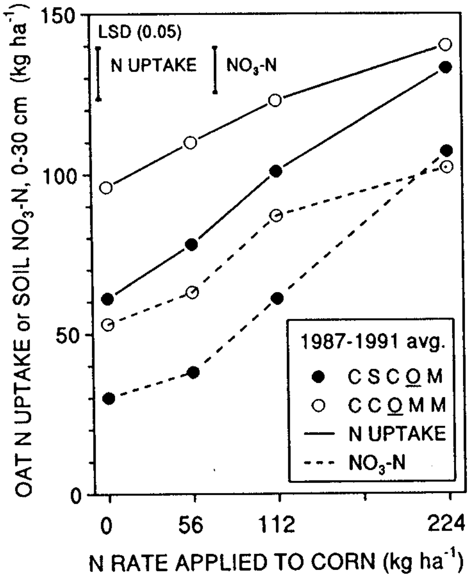

Fig. 2. Soybean effect on soil NO_3–N content (0 to 30 cm) and total oat N uptake at various corn N fertilizer rates. Each point is a mean of 10 observations over 5 yr. LSD applies for comparisons between any two means.

nomenon may be related to cycling of N between crop residues and soil organic N fractions and/or to changes in soil and plant biological activity. Our data do not indicate whether this soil-N depletion occurred at the soybean phase or at the 1st-yr corn phase. In both cases, N availability is increased for 1st-yr cereal crops following soybean and reduced in the 2nd yr due to depletion of the soil's available N pool. Reduced N availability in the 2nd yr following soybean is consistent with N budget studies (e.g., Heichel and Barnes, 1984) showing that soybean removes more N from the soil than is fixed symbiotically. The positive N effect observed with 1st-yr corn following soybean (Table 1) is probably due to N released from soybean residues, and represents a recycling of the soil N accumulated in these residues. The N in soybean residues is rapidly mineralized and is usually taken up almost completely by subsequent corn (Power et al., 1986).

Our results also support the hypothesis that soybean production may enhance soil N mineralization and subsequent N uptake by 1st-yr corn through increased biological activity or shifts in soil microbial populations. For example, Yaacob and Blair (1980) found that the addition of soybean residues to soil increased uptake of native soil organic N by rhodesgrass (*Chloris gayana* Kunth) in a greenhouse study. Enhanced N availability has also been attributed to root-induced N mineralization (Clarholm, 1985, 1989), in which C released into the soil from roots enhances the availability of soil N to plants by stimulating microbial cycling. The possibility that the soybean sequence effect could result from changes in the type of microorganisms colonizing the corn rhizosphere is supported by the work of Fryson and Oaks (1990), who observed a significant corn growth response when pots containing corn plants were inoculated with a variety of the legume soils, including soybean. No growth response was detected when legume–soil inoculants were sterilized or when soils previously used for corn production were used as the inoculant. Recent work (Onyango and Clegg, 1993) involving residue removal and transfer following corn and soybean production suggests that both N mineralization from soybean residue and enhanced soil N availability contribute to increased N availability to 1st-yr corn following soybean.

CONCLUSIONS

Our results indicate that the N cycle processes involved in the N contribution of soybean to a following corn crop are different from those associated with alfalfa N contributions. The reduction in soil-N availability observed the 2nd yr following soybean suggests that part of the N contribution of soybean to 1st-yr corn is realized at the expense of subsequent reductions in soil N availability. It is possible that soybean production stimulates soil microorganisms that enhance soil N mineralization and corn uptake in the 1st yr following soybean resulting in a depletion of readily available soil N in the 2nd yr after soybean. Further research is needed to study N dynamics in soybean-corn crop sequences and the biology involved in the soybean rotation effect.

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